Enhancing Water Use Efficiency in Irrigated Agriculture

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ABSTRACT

Irrigated agriculture is a vital component of total agriculture and supplies many of the fruits, vegetables, and cereal foods consumed by humans; the grains fed to animals that are used as human food; and the feed to sustain animals for work in many parts of the world. Irrigation worldwide was practiced on about 263 Mha in 1996, and about 49% of the world's irrigation occurred in India, China, and the USA. The objectives of this paper are to (i) review irrigation world-wide in its ability to meet our growing needs for food production, (ii) review irrigation trends in the USA, (iii) discuss various concepts that define water use efficiency (WUE) in irrigated agriculture from both engineering and agronomic viewpoints, and (iv) discuss the impacts of enhanced WUE on water conservation. Scarcely one-third of our rainfall, surface water, or ground water is used to produce plants that are useful to mankind. Without appropriate management, irrigated agriculture can be detrimental to the environment and endanger sustainability. Irrigated agriculture is facing growing competition for low-cost, high-quality water. In irrigated agriculture, WUE is broader in scope than most agronomic applications and must be considered on a watershed, basin, irrigation district, or catchment scale. The main pathways for enhancing WUE in irrigated agriculture are to increase the output per unit of water (engineering and agronomic management aspects), reduce losses of water to unusable sinks, reduce water degradation (environmental aspects), and reallocate water to higher priority uses (societal aspects).

I RRIGATION IS VITALLY IMPORTANT in meeting the food and fiber needs for a rapidly expanding world population that reached six billion on 12 Oct. 1999 and is currently increasing by about 80 to 85 million people each year. The United Nations projects that the world population in 2050 could be 7.3 to 10.7 billion if reproductive fertility declines and 14.4 billion if the world's population continues to increase at its present rate. Much of this growth will occur in the developing world. If the current growth rate in Africa is maintained, its population will double in <25 yr. While most demographers expect human reproductive fertility rates to decline, the population in south-central Asia is projected to double in 30 yr, and Central America's population could double in 35 yr. The income of much of the increased population and its consumption of goods and services has also increased, increasing the pressure on natural resources (soil and water) and energy supplies. While this income provides adequate nutrition for people in some regions, significant and even worsening malnutrition problems exist in others.

This symposium is devoted to understanding mechanisms that could achieve the higher WUE that will allow the world's food production to keep pace with its growing population, if that is even possible. Sinclair et al. (1984) described WUE on various scales from the leaf to the field. In its simplest terms, it is characterized as crop yield per unit of water use. At a more biological level, it is the carbohydrate formed through photosynthesis from CO_2, sunlight, and water per unit of transpiration. Brown (1999) has proposed that the upcoming benchmark for expressing yield may be the amount of water required to produce a unit of crop yield, which is simply the long-used *transpiration ratio*, or the inverse of WUE. Often the term WUE becomes confounded when used in irrigated agriculture. Bos (1980, 1985) recommended that WUE for irrigation be based on the yield produced above the rainfed or dryland yield divided by the *net* evapotranspiration (ET) difference for the irrigated crop, which he called the yield/ET ratio. He also proposed the irrigated difference from the dryland yield divided by the *gross* applied water, which he called the yield/water-supply ratio and is referred to as irrigation WUE (I_{WUE}) in this paper. These definitions are attractive but difficult to apply because many management factors such as fertility, variety, pest management, sowing date, soil water content at planting, planting density, and row spacing could affect yield or differ substantially between irrigated and dryland agriculture. Defining WUE for irrigation is additionally complex because the scale of importance for the water resource shifts to the broader hydrologic, watershed, irrigation district, or irrigation project scale, and the water components may not be so precisely defined, becoming even more qualitative when such terms as *reasonable, beneficial*, or *recoverable* are used (Burt et al., 1997). The objectives of this paper are to (i) review irrigation world-wide in its ability to meet our growing needs for food production, (ii) review irrigation trends in the USA, (iii) discuss various concepts that define WUE in irrigated agriculture from both engineering and agronomic viewpoints, and (iv) discuss the impacts of enhanced WUE on water conservation. Irrigation can be an effective means to improve WUE through increasing crop yield, especially in semiarid and arid environments. Even in subhumid and humid environments, irrigation is particularly effective in overcoming short-duration droughts. However, irrigation by itself may not always produce the highest WUE possible. Agronomists have long been

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Abbreviations: ET, evapotranspiration; ET_d, evapotranspiration for an equivalent dryland or rainfed only plot; ET_i, evapotranspiration for irrigation level i; ET_{WUE}, evapotranspiration water use efficiency; FAO, Food and Agriculture Organization; I_{WUE}, irrigation water use efficiency; LEPA, low-energy precision application; P, precipitation; WUE, water use efficiency; Y_d, yield for an equivalent dryland or rainfed only plot; Y_i, yield for irrigation level i.

Table 1. World population and irrigated land [sources: Rhoades, 1997; Ghassemi et al., 1995; Worldwatch Inst., 1999; and Food and Agric. Organ. of the United Nations (FAOSTAT), 1999].

Year	Population	Irrigated area	Per capita irrigated area
	billions	Mha	ha person^{-1}
1800	~1	8	0.008
1900	1.5	40	0.027
1950	2.5	94	0.038
1961	3.1	139	0.045
1965	3.7	151	0.045
1970	4.1	169	0.046
1975	4.4	190	0.047
1979	4.4	209	0.048
1980	4.9	211	0.047
1985	5.3	226	0.046
1990	5.6	239	0.045
1994	5.7	249	0.044
1996		263	0.046

at the forefront of research on irrigated agriculture as chronicled in articles like the ASA presidential address by D.W. Robertson in 1952 (Robertson, 1952), the agronomy monographs on irrigation (Hagan et al., 1967; Stewart and Nielsen, 1990), and books and symposia on efficient water use (Taylor et al., 1983; Pierre et al., 1966). Readers are also referred to important review articles on irrigated agriculture like Clothier (1983), Clothier and Green (1994), and Pereira et al. (1996). Although much has changed with irrigation water management and irrigation technology in the past 20 yr, Dr. Marvin Jensen's comment, "The greatest challenge for agriculture is to develop the technology for improving water use efficiency," (Karasov, 1982) remains true today.

WORLD POPULATION AND IRRIGATION TRENDS

As the world's population has increased since the 1960s, irrigated land area has also increased such that the per capita irrigated land has remained relatively stable at about 0.045 ha person^{-1} (Table 1). In contrast, arable land area per capita has decreased from 0.38 ha person^{-1} in 1970 to 0.28 ha person^{-1} in 1990 (FAOSTAT, 1999). Worldwide irrigated land covered about 263 Mha (FAOSTAT, 1999) in 1996 (Table 1). Irrigated land comprises 15% of the arable land in the world and produces 36% of the food [Food and Agricultural Organization (FAO), 1988]. Two-thirds of the world's irrigated area is in Asia (Table 2). Nearly 70% of the grain in China and almost 50% of the grain in India is harvested from irrigated lands (Brown, 1999). The FAO (1988) estimated that almost two-thirds of the increase

in crop production that is needed in developing countries in the upcoming decades must come from an increased yield per unit of land area; one-fifth must come from increased arable land area and the remaining one-eighth from increased cropping intensity. The FAO attributes almost two-thirds of the increase in arable land to increased irrigated land. Rhoades (1997) similarly concluded that the required increased food production in developing countries must come primarily from irrigated land.

Asia has a high percent of the world's irrigated land (Table 2), and its percent change from 1974 to 1989 was similar to the change worldwide. In projecting global water demands, Seckler et al. (1998) concluded that one-half of the increase in the demand for water by 2025 could be met by increasing the effectiveness of irrigation. While the remaining water needs could be met by small dams and the conjunctive use of aquifers, medium-sized dams will certainly be needed. Postel (1993) noted the slow worldwide irrigation expansion since the 1970s, which barely averaged 1%, and attributed this to declining international lending and the long lead time for new projects. In addition, escalating costs for irrigation projects have made such investments difficult to justify. The rate of change (slope) in irrigated land exceeded the worldwide population growth rate until 1980 (Fig. 1). Also, environmental concerns caused by irrigation raise serious questions and pose difficult problems in many parts of the world with regards to irrigation sustainability (Rhoades, 1997). Rhoades (1997) quoted Ghassemi et al. (1995) and others who estimated that around 40 to 50 Mha of irrigated lands may already be degraded by waterlogging, salinization, and sodication.

IRRIGATION TRENDS IN THE USA

Gardner et al. (1996) and Vaux et al. (1996) provided current reviews of U.S. irrigation. The irrigated area in the USA since 1969 is now rather stable at around 20 Mha (Fig. 2). However, annual irrigation applications have declined from 650 mm of applied water in the early 1970s to about 500 mm in recent years. This represents improved and careful management and improved irrigation systems. Jensen et al. (1990) gave a more thorough discussion of global irrigation advances and a regional breakdown of U.S. irrigation development. Many factors are involved in irrigation expansion or decline in the USA, including problems of waterlogging and salini-

Table 2. Irrigated area by continent (adapted from Gleick, 1993).

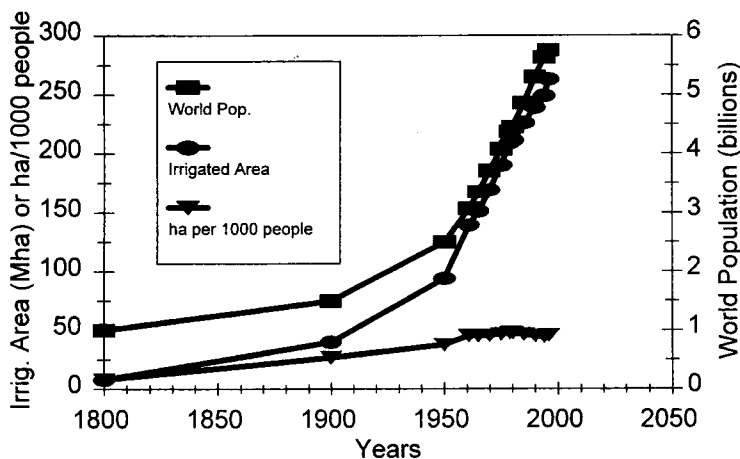| Continent	1974	1979	1984	1989	Change in irrigated area (1974–1989)	1989 per capita irrigated area
	Mha				%	ha person^{-1}
World	185	209	221	233	26	0.045
Africa	9	10	11	11	20	0.018
North and Central America	23	28	25	26	15	0.061
South America	6	7	8	9	39	0.030
Asia	119	132	140	146	23	0.048
Europe	13	14	16	17	37	0.035
Oceania	1.6	1.7	1.9	2.1	24	0.083
USSR	14	17	19	21	54	0.074

Fig. 1. Illustration of the growth of the world's population, irrigated area, and irrigated land per person. Data were taken from several sources, including Rhoades (1997), Ghassemi et al. (1995), Worldwatch Institute (1999), and Food and Agriculture Organization of the United Nations [FAOSTAT] (1999).

zation as well as other water quality degradation issues (Rhoades, 1997; Jensen et al., 1990).

Since 1992, irrigated land area in the USA has increased 2.28 Mha (USDC, 1999) (Fig. 3). Interestingly, several pockets of irrigation expansion have occurred along the Mississippi Delta region from northeast Louisiana to southern Missouri, in the western Texas High Plains, across eastern Nebraska, in the San Luis Valley in south-central Colorado, and throughout the Central Valley of California. The northwest USA and the intermountain West also showed widespread expansion although not as concentrated. This net expansion is rather significant, representing almost 10% of the irrigated land in the USA.

Irrigation decline also seemed clustered in areas such as southern Florida; southwestern Georgia; the rice (*Oryza sativa* L.) belt in Texas and Louisiana; the lower Rio Grande Valley of Texas; Hawaii; and the central plains regions from the northeastern Texas Panhandle, Oklahoma Panhandle, Southwest Kansas, and parts of Colorado. Although the 1997 agricultural census (USDC, 1999) doesn't specify the commodity area changes as to irrigated and nonirrigated crops, it is apparent that in the Mississippi Delta, rice and soybean [*Glycine max* (L.) Merr] increased and cotton (*Gossypium hirsutum* L.) decreased. Cotton and peanut (*Arachis hypogaea* L.)

increased in the southwestern High Plains of Texas (Dawson and Gaines counties), and irrigated corn (*Zea mays* L.) increased in both the northwestern Texas Panhandle (Dallam county) and Nebraska where soybean also increased. Irrigated potato (*Solanum tuberosum* L.) production has likely increased substantially during this period in the San Luis Valley of Colorado and across Idaho, Washington, and Oregon. Although irrigated cotton area declined in Mississippi, it increased across Georgia and the Carolinas due to improved boll weevil (*Anthonomus grandis grandis*) control. The majority of the increases in grain sorghum [*Sorghum bicolor* (L.) Moench] area were in southwestern Kansas and were likely irrigated. Irrigated grain production remains important for the continued increase in cattle feeding in Texas, western Kansas, Nebraska, and northeastern Colorado. Dairy migrations from southern California to the Central Valley in California, eastern New Mexico, and south-central Idaho occurred in the period between 1992 and 1997.

During the period between 1964 and 1997, total cropland declined from 185 to 175 Mha while harvested cropland increased from 116 to 122 Mha (USDC, 1999)
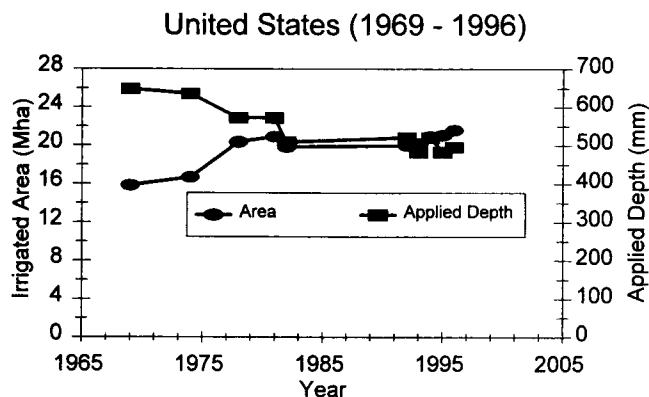

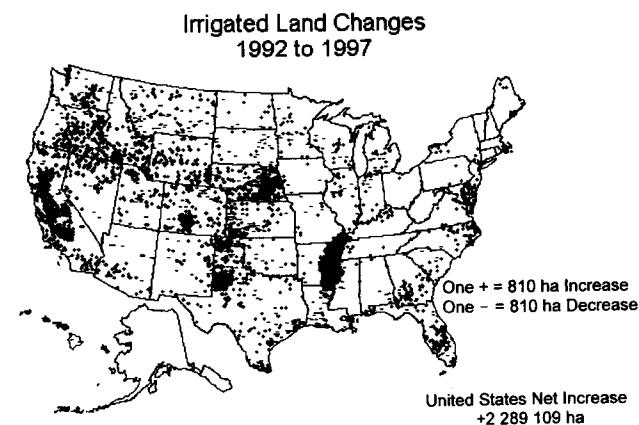Fig. 2. Trend in U.S. irrigated areas since 1969 (ERS, 1997).

Fig. 3. Changes in U.S. irrigated land since the 1992 agricultural census, indicating a net increase of 2.89 Mha (USDC, 1999). Illustration was supplied by the USDA-NASS, Washington, DC.
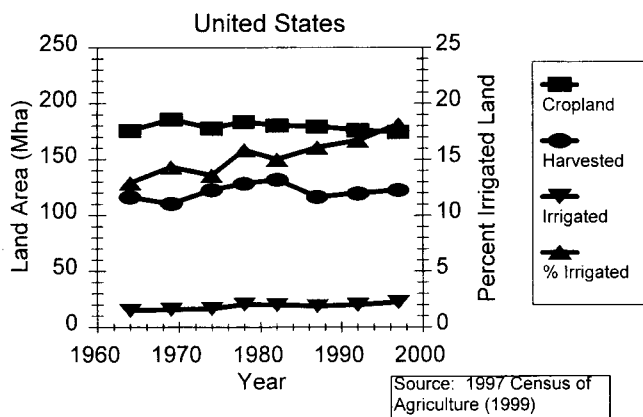
Fig. 4. Planted and irrigated cropland in the USA and the percent of cropland that was irrigated since 1964 (USDC, 1999).

(Fig. 4). Irrigated land area increased from 15 to 22 Mha during this period. The percentage of U.S. cropland that is irrigated increased from almost 13% in 1964 to more than 18% in 1997 (USDC, 1999). This percentage is almost exactly the same as the world value. Remarkably, this small fraction of U.S. farmland produced almost 50% of the total value of crops in 1997 (USDC, 1999) (Fig. 5). The high percentage of irrigation used in orchards and for vegetables, potato, hay [especially alfalfa (*Medicago sativa* L.)], and cotton has contributed to the importance of irrigation in U.S. agricultural production (Table 3).

The types of irrigation systems used have changed dramatically through the years. Surface irrigation (various gravity methods) decreased from 63% of the total in 1979 to 50% in 1994 (ERS, 1997) (Fig. 6) while low-pressure systems (e.g., drip, trickle, and microsprays) increased from 0.6% of the total in 1979 to almost 4% in 1994. One of the larger and more obvious changes was to center pivot sprinklers. Although subirrigation accounts for a rather insignificant amount, it is important in areas where subsurface drainage involving watertable control technology is used to improve crop performance as well as water quality (Fig. 7). Of course,
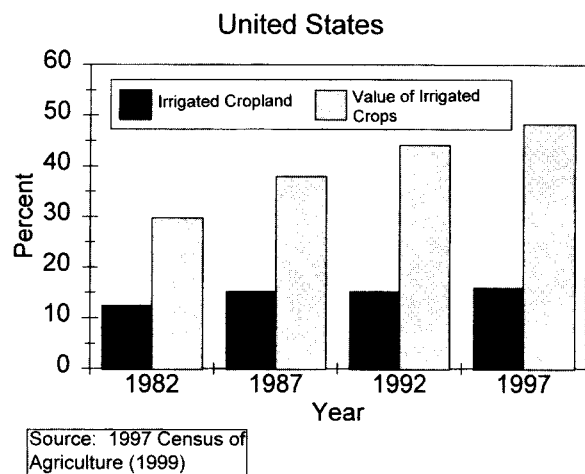
Table 3. Percentage of selected crops produced in the USA with irrigation during 1992 (ERS, 1997).

Crop	Irrigated production	Irrigated area
	%	Mha
Rice	100	1.3
Orchards	76	–
Potato (Irish)	71	0.4
Vegetables	65	1.0
Cotton	34	1.5
Corn (grain)	14	3.9
All hay	15	3.5
Wheat	7	1.7

the huge percentage increase in drip systems (and other low-pressure systems) stems from their small quantity.

ENHANCING FIELD WATER USE EFFICIENCY IN IRRIGATED AGRICULTURE

These irrigation statistics demonstrate the important role that irrigated agriculture has in both the USA and the world; they also demonstrate the need to enhance WUE in irrigated agriculture. Although the crop species, genotype, and available energy from sunlight are vitally important to WUE (primarily through the CO_2 pathway), water is often the critically important element in agriculture. Water is important in rainfed agriculture, critically important in semiarid dryland agriculture, and explicitly important in irrigated agriculture. Wallace and
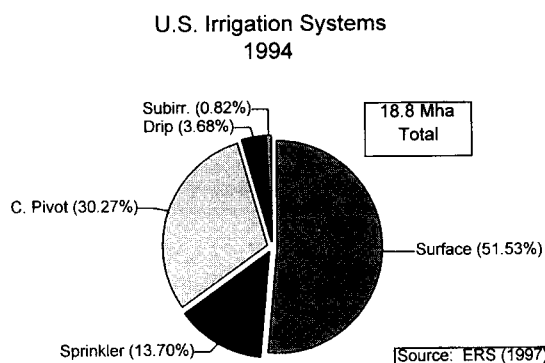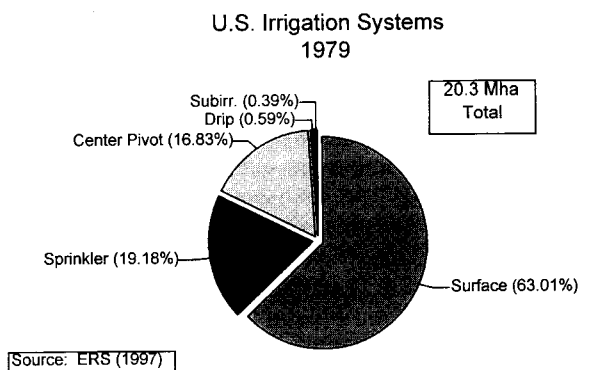

Fig. 5. Change in the percent of U.S. cropland and crop production that is irrigated (USDC, 1999).

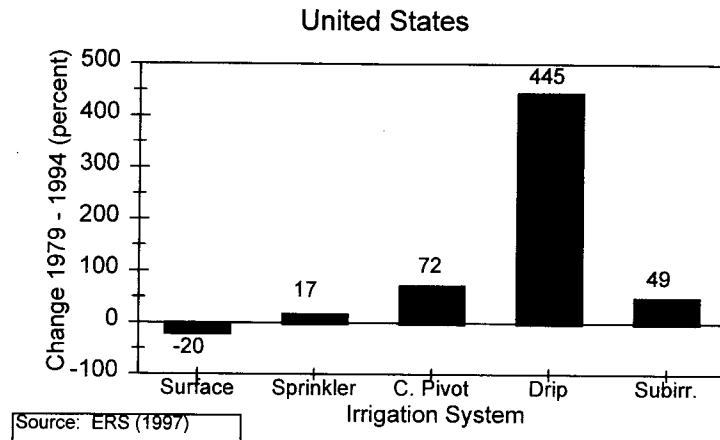**Fig. 6. Irrigation systems in use in the USA in 1979 and 1994.**

Fig. 7. Percentage changes in irrigation systems in the USA from 1979 to 1994 (ERS, 1997).

Batchelor (1997) offered four options for enhancing WUE in irrigated agriculture (Table 4). They point out that focusing on only one category will likely be unsuccessful.

Water use efficiency is generally defined in agronomy (Viets, 1962) as

$$\text{WUE} = \frac{\text{Crop yield (usually the economic yield)}}{\text{Water used to produce the yield}} \quad [1]$$

If the crop yield is expressed in g m^{-2} and the water use is expressed in mm, then WUE has units of kg m^{-3} on a unit water volume basis or g kg^{-1} when expressed on a unit water mass basis. Although useful in many analyses, WUE doesn't take into account the role of irrigation. Bos (1980, 1985) developed expressions that can, perhaps, more consistently discriminate the role that irrigation has in WUE. His expressions can be written for ET$_{\text{WUE}}$ and I$_{\text{WUE}}$ as

$$\text{ET}_{\text{WUE}} = \frac{(Y_i - Y_d)}{(ET_i - ET_d)} \quad [2]$$

$$\text{I}_{\text{WUE}} = \frac{(Y_i - Y_d)}{I_i} \quad [3]$$

where Y_i is the yield and ET_i is the ET for irrigation level i, Y_d is the yield and ET_d is the ET for an equivalent dryland or rainfed only plot, and I_i is the amount of irrigation applied for irrigation level i. Of course in most arid areas, Y_d would be zero or small; however, ET_d could be much greater than zero and variable depending on the agronomic practices. In semiarid and rainfed areas, Y_d could be determined several ways. In the strictest sense, it would be the yield under exactly the same management as the i treatment or system but without irrigation. In a more comparative system, it might be estimated by yields from comparable dryland or rainfed plots that were not irrigated. Often, however, agronomic practices differ substantially between dryland and/or rainfed and irrigated practices (e.g., variety, sowing date, fertility management, pest management, sowing density, and planting geometry). Thus, results that are quite different might be obtained for Y_d and ET_d based on differences in management.

The water use in Eq. [1] is difficult to determine precisely. So, in some situations, a benchmark WUE (WUE$_b$) is used by many irrigation practitioners. It can be defined as

$$\text{WUE}_b = \frac{\text{Yield (usually the economic yield)}}{(P_e + I + SW)} \quad [4]$$

where P_e is *effective* rainfall, I is irrigation applied, and SW is soil water depletion from the root zone during the growing season. The denominator of Eq. [4] is a surrogate estimate for the water used to produce the crop, depending on the neglect of percolation, ground water use, and surface runoff. Experienced practitioners can use Eq. [4] for a specific region and to identify differences between irrigation methods, irrigation management, or both.

Howell et al. (1990) presented an expression for field WUE based on Cooper et al. (1987) and Gregory (1990) as

Table 4. Examples of options available for improving irrigation efficiency at a field level adapted from Wallace and Batchelor (1997).

Improvement category	Options
Agronomic	crop management to enhance precipitation capture or reduce water evaporation (e.g., crop residues, conservation till, and plant spacing); improved varieties; advanced cropping strategies that maximize cropped area during periods of lower water demands and/or periods when rainfall may have greater likelihood of occurrence.
Engineering	irrigation systems that reduce application losses, improve distribution uniformity, or both; cropping systems that can enhance rainfall capture (e.g., crop residues, deep chiseling or paratilling, furrow diking, and dammer-diker pitting).
Management	demand-based irrigation scheduling; slight to moderate deficit irrigation to promote deeper soil water extraction; avoiding root zone salinity yield thresholds; preventive equipment maintenance to reduce unexpected equipment failures.
Institutional	user participation in an irrigation district (or scheme) operation and maintenance; water pricing and legal incentives to reduce water use and penalties for inefficient use; training and educational opportunities for learning newer, advanced techniques.

$$\text{WUE} = \frac{(HI \times DM)}{\left[T(1 - WC)\left[1 + \dfrac{E}{(P + I + SW - D - Q - E)} \right] \right]} \quad [5]$$

where HI is the harvest index (dry yield per unit dry matter), DM is dry matter in g m^{-2} (it has to be the same as the dry matter component used to calculate the harvest index whether it is aboveground dry matter or total dry matter, including roots), T is transpiration in mm, WC is the standard water content used to express the economic yield (in a fraction; i.e., 0.15–0.155 is common for corn and 0.14 is common for other cereals), E is soil water evaporation in mm, P is precipitation in mm, I is irrigation in mm, SW is soil water depletion from the root zone in mm, D is deep percolation below the root zone in mm, and Q is surface runoff in mm. In some cases, other water balance components may need to be considered such as crop interception, surface runon, or upward flow from ground water into the root zone. Equations [1], [4], and [5] illustrate the common problems encountered in accurately assessing WUE from field measurements. Both P and I may contribute water to Q, making estimates of effective precipitation, P_e, difficult to determine in some cases. Likewise, both P and I may contribute or cause water to move past the crop root zone, resulting in difficulties in characterizing D. Profile soil water depletion can be measured, but it typically can only be determined at a few discrete points in a plot or field. The stochastic distribution of P across a plot or field is often ignored together with the distribution of I, which is known to be more predictable but still probabilistic. All of these spatial variations impact ET and SW. To obtain reproducible and reliable estimates for P, I, Q, D, and SW to estimate ET in Eq. [1] or [2], extreme measures like plot leveling and bordering may be required. These techniques, although widely used in arid and semiarid experiments, may be impractical in many situations or induce undesired effects on ET_d or Y_d, particularly in higher rainfall regions. They may even affect D in those cases both by changing the profile soil water balance and by leaching crop nutrients from the root zone, thereby affecting Y_i.

Equation [5] represents all of the agronomic and engineering mechanisms offered by Wallace and Batchelor (1997) to enhance WUE. These are (i) increasing the harvest index through crop breeding or management; (ii) reducing the transpiration ratio (T/DM) by improved species selection, variety selection, or crop breeding; (iii) maximizing the dry matter yield through enhanced fertility, disease and pest control, and optimum planting; and/or (iv) increasing the transpiration component relative to the other water balance components. In particular, Element iv might be obtained by reducing soil water evaporation by increasing residues, shallow mulch tillage, alternate furrow irrigation, or narrow row planting; reducing deep percolation below the root zone by avoiding overfilling the root zone and minimizing leaching to the absolute minimum for salinity control; and reducing surface runoff by using furrow

diking, dammer diking, crop residues, or avoiding soil compaction and hardpan problems while increasing soil water depletion from the profile by gradually imposing soil water deficits, deeper soil wetting, or by using deeper-rooted varieties. Although both Elements i and ii are biologically controlled and difficult to manipulate, some diversity and variability may exist in the field that can be controlled. Element iii is the current focus of much research in precision agriculture to enhance yields relative to needed inputs at the correct time and location in the field. Element iv is the basis of almost all current water conservation technologies to enhance rainfall capture and improve irrigation technologies to avoid or minimize application losses.

Engineers have long characterized irrigation performance using various efficiency and uniformity terms (Burt et al., 1997). Wang et al. (1996) offered a new efficiency term, called the general efficiency (E_g), based on the ratio of transpiration to the sum of the volume of applied water and the volume of the deficit expressed as

$$E_g = \frac{\alpha E_a E_s}{(E_a + E_s - E_a E_s)} \quad [6]$$

where E_g is the general irrigation efficiency fraction, α is the transpiration fraction of ET (T/ET), E_a is the application efficiency fraction (volume of water stored in the root zone per unit of water volume delivered to the field), and E_s is the storage efficiency fraction (volume of water stored in the root zone per unit of water volume needed in the crop root zone). Equation [6] is related to Eq. [5] without the yield parameters that have become integral in WUE. It clearly emphasizes, like Wallace and Batchelor (1997), the need to maximize transpiration while minimizing application losses and meeting the water needs of the crop. Wang et al. (1996) believed that E_g would be more closely associated with crop yield than the individual efficiency terms because it could simultaneously consider both deep percolation losses and irrigation deficits while excluding the soil water evaporation loss that may not directly contribute to crop yield. Equation [6] can be applied to differing irrigation scales from plots to watersheds although like all efficiency characterizations (Burt et al., 1997), the various water components remain challenging to measure in the field.

Examples

The WUE, ET$_{\text{WUE}}$, and I$_{\text{WUE}}$ values for corn at Bushland, TX varied dramatically between irrigation application methods and water management treatments (Table 5). Several items from these data are evident: (i) I$_{\text{WUE}}$ is typically much greater than just WUE; (ii) both WUE and I$_{\text{WUE}}$ do not differ greatly among irrigation methods when operated to avoid and/or minimize application losses; (iii) I$_{\text{WUE}}$ generally tends to increase with a decline in irrigation if that water deficit does not occur at a single growth period [i.e., see the surface data with specific period deficits (likely attributed to enhancing the transpiration component in relation to total water use)];

(iv) both WUE and I_{WUE} for corn at Bushland, TX are maximized with a small water deficit (likely attributed to reducing unnecessary soil water evaporation while not reducing transpiration) while ET_{WUE} generally is highest with less irrigation, implying full use of the applied water and perhaps a tendency to promote deeper soil water extraction to make better use of both the stored soil water and the growing-season rainfall. Tanner and Sinclair (1983) presented data that supported their concept of greater corn WUE in more-humid environments. Their mean WUE was 1.8 kg m^{-3} for several western sites while averaging >2.5 kg m^{-3} in more-humid sites. The WUE values for corn at Bushland, TX are lower than values in Tanner and Sinclair (1983; their Table 5), reflecting the greater vapor pressure deficit and evaporative demand for corn in the southern High Plains. However, this region has some of the nation's highest mean county corn yields (NASS, 1999; NASS, 1999). For example, Dallam County in Texas averaged 12.8 Mg ha^{-1} on >61 100 ha in 1998, which was a drought year, (NASS, 1999) compared with the best county in Iowa in 1998, Scott County, which averaged 10.6 Mg ha^{-1} on >47 100 ha (NASS, 1999). Interestingly, the higher Bushland I_{WUE} values approached the 2.5 kg m^{-3} values for WUE in the more-humid sites, indicating the greater effectiveness of the applied irrigation component of the total water balance. The mean ET_{WUE} from these experiments was 2.49 kg m^{-3}, which was essentially the same as the humid-site WUE value of 2.5 kg m^{-3} from Tanner and Sinclair (1983). The higher ET_{WUE} values compared with the I_{WUE} values at near maximum ET or irrigation indicated that either the extra water was not used by the crop or the rainfall combined with the irrigation was ineffective. In almost every case, a slight under irrigation (about 0.75–0.8 of full irrigation or withholding early vegetative irrigations) maximized WUE, ET_{WUE}, and I_{WUE}. The main exception was the high ET_{WUE} and I_{WUE} values for the low-energy precision application (LEPA) irrigated corn for the lower irrigation fractions. This may be attributed to the effects of the furrow dikes used with LEPA to reduce water redistribution on the plot surface or surface runoff despite the drip and surface plots being leveled and bordered.

ENHANCING WATERSHED OR IRRIGATION DISTRICT WATER USE EFFICIENCY IN IRRIGATED AGRICULTURE

On-farm irrigation technology can most certainly be enhanced as discussed in the prior section. However, these increases in WUE and reductions in water loss only have economic consequences depending on the cost of the water and if any environmental costs are assigned to the degradation or depletion of the water resource (Carter et al., 1999). The savings of any water will depend on whether the watershed or basin is closed (no usable water leaves the basin or project) or open (when usable water does leave the basin or project). Agriculture consumes >80% of the world's developed water supplies. Traditional gravity systems may have an

Table 5. Examples of water use efficiency (WUE), evapotranspiration water use efficiency (ET$_{WUE}$), and irrigation water use efficiency (I$_{WUE}$) values for corn irrigated by surface (level basins), low-energy precision application (LEPA), and drip/microirrigation (subsurface drip and surface drip) (Musick and Dusek, 1980; Howell et al., 1995; and Howell et al., 1997, respectively) at Bushland, TX. The data were averaged for 2 yr.

Irrigation method	Irrigation fraction	WUE†	ET$_{WUE}$	I$_{WUE}$‡
			kg m^{-3}	
Surface	Full	1.35	2.66	2.41
(level basins)	Vegetative deficit	1.23	3.01	2.53
1976 and 1977	Pollination deficit	0.91	1.97	1.98
	Grain-filling deficit	1.11	1.96	2.06
	0.00	0.00	–	–
LEPA	1.00	1.35	2.13	1.73
1992 and 1993	0.80	1.45	2.56	2.07
	0.60	1.38	2.59	2.01
	0.40	1.38	3.06	2.36
	0.20	1.28	3.85	2.10
	0.00	0.93	–	–
Subsurface drip	1.00	1.42	1.98	1.79
1993 and 1994	0.67	1.53	2.43	2.35
	0.33	1.21	2.37	2.28
	0.00	0.43	–	–
Surface drip	1.00	1.39	1.95	1.78
1993 and 1994	0.67	1.52	2.37	2.28
	0.33	1.23	2.42	2.35
	0.00	0.43	–	–

† Yields based on 15.5% grain water content.
‡ Preplant irrigations were excluded.

efficiency of only 40% (Seckler, 1996) and use a large fraction of the freshwater withdrawals, particularly in most western U.S. states. Any increase in use effectiveness is perceived to free up water for other users. This argument is frequently used in municipal vs. agriculture battles (legal or just verbal ones). These water losses or gains (depending on your side of the argument) have been called *wet* or *real* losses or *dry* or *paper* losses (Seckler, 1996; Keller et al., 1996). Willardson et al. (1994) and Allen and Willardson (1997) favored avoiding the term irrigation efficiency and instead defined the fraction of water that was consumed, unavailable to other users, and returned to the hydrologic system for reuse. Several factors need to be considered if the water must be lifted (pumped) for reuse (as is the typical case with tailwater recycling schemes) or if there are any operational costs for water treatments (e.g., trash removal and filtration).

When water is diverted within a basin for irrigation, three *basic* losses can result: (i) part of the water is consumed in evaporation (e.g., from canals or crops); (ii) a portion percolates to surface or subsurface areas (e.g., canal seepage or root zone deep percolation) where some is inherently lost so that it cannot be recaptured (e.g., in the unsaturated vadose zone, the ocean, or a salt sink) while some may be recaptured (e.g., interceptor drains into a drainage canal or a drainage well) and can still be used as an additional supply; or (iii) the drainage water becomes polluted from salts or chemicals (e.g., nutrients or pesticides) that are so concentrated that the water is no longer usable and must be discharged to a sink for disposal. In an open system with plentiful water, few problems exist or develop. The main problem might be the capture and distribution of this water and excessive irrigations leading to waterlogging,
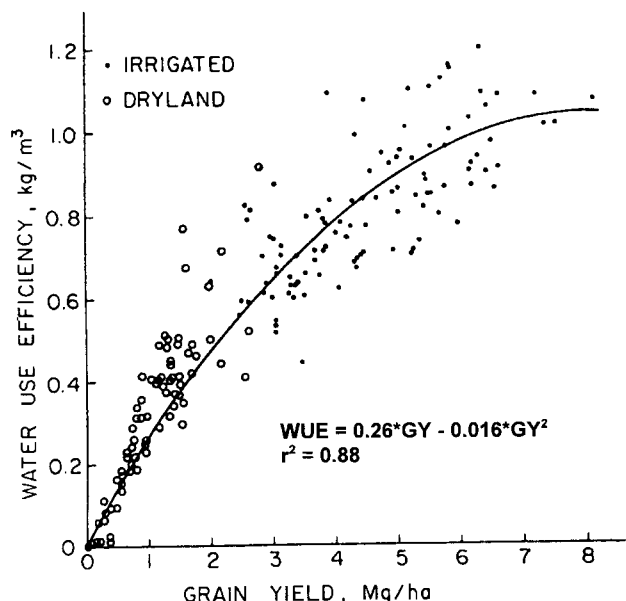
Fig. 8. Relationship between winter wheat yield and water use efficiency (WUE) at Bushland, TX (Musick et al., 1994).

salinization, or both. However, as the basin approaches a closed state where all usable water is captured and allocated, all that remains is the consumed water and the water that is so polluted that it cannot be used. This latter problem is very common and pits the head-end (close to diversion point) people against the tail-end (low end of the system) people or the senior right (first priority) holders against the junior right (lowest priority) holders. In essence, only a reduction in consumption or in the amount that is lost to a sink can be considered as conserved water. In some cases, enhanced WUE results in more water consumption, and a higher irrigation efficiency can result in less water being available in the basin.

Examples

Irrigation in the Texas High Plains is primarily from the Ogallala Aquifer (known as the High Plains aquifer), which is essentially a closed basin (minimum recharge and small stream flow exports). Many technologies have improved the efficiency of on-farm irrigation application (Musick and Walker, 1987) and reduced mean annual application depths. Crop yields have increased as well (NASS, 1999) due to enhanced agronomic practices like improved varieties, fertility, and pest control [see Musick et al., 1994 for winter wheat (*Triticum aestivum* L.)]. However, WUE in this region has increased for wheat (Fig. 8; Musick et al., 1994) and corn (Howell and Tolk, 1998; data not shown) mainly in response to irrigation (both curvilinear due to the yield ET offset). If the irrigated area was constant or reduced, then the *dry* water savings (those projected based on increasing irrigation efficiency or the consumed fraction) could be converted into *wet* water savings (real water conservation). Otherwise, the improved irrigation efficiencies simply permit irrigated land to be expanded (in a nonlimited arable land situation) as is

likely the case for most of the new irrigation in the Texas High Plains (Fig. 3). Some water districts are imposing strict regulations on new wells in this region that effectively reduce ground water depletion and conserve *wet* water.

Allen and Willardson (1997) provide several interesting examples of open systems in eastern Idaho that traditionally have low irrigation efficiency and small actual water consumption. These irrigation projects (districts) divert considerably more water than is consumed by the crops, and substantial amounts of water seep into the ground water and/or return back to the Snake River for downstream diversion by other users or projects. This multiple reuse from the irrigation-induced recharge in Idaho was noted to improve river fisheries ($80 million yr^{-1}); enhance hydropower production, especially during low-flow periods ($20 million yr^{-1}); reduce river flooding; and reduce pumping lifts from the aquifer. Allen and Willardson (1997) noted the problem of reduced irrigation diversions for junior permit holders downstream and the reduced flushing (removal of sediment buildups) of the Snake River during the months of high river flow.

SUMMARY

Irrigation remains vitally important in the USA and worldwide as a means to enhance production and increase WUE. Many agronomic, engineering, and management technologies can reduce nonproductive water use in irrigated agriculture. However, in some cases, increasing irrigation efficiencies may not simply achieve new water for allocation unless the consumptive use part of the diverted water is actually reduced. Seckler (1996) summarized these opportunities as (i) increasing the output per unit of ET (essentially WUE), (ii) reducing losses of usable water to sinks, (iii) reducing water pollution (from sediments, salinity, nutrients, and other agrochemicals), and (iv) reallocating water from lower-valued to higher-valued uses. The latter opportunity can be positive or negative to agriculture depending on how secondary and tertiary interest holders are addressed.

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